

Production of keV Sterile Neutrinos in Supernovae: New Constraints and Gamma Ray Observables

Carlos A. Argüelles,^{1,2} Vedran Brdar,³ and Joachim Kopp³

¹*Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

²*Wisconsin IceCube Particle Astrophysics Center, Madison, WI 53703, USA*

³*PRISMA Cluster of Excellence, 55099 Mainz, Germany and*

Mainz Institute for Theoretical Physics, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany

We study the production of sterile neutrinos in supernovae, focusing in particular on the keV–MeV mass range, which is the most interesting range if sterile neutrinos are to account for the dark matter in the Universe. We argue that in this mass range, the production of sterile neutrinos can be strongly enhanced by a Mikheyev–Smirnov–Wolfenstein (MSW) resonance, so that a substantial flux is expected to emerge from a supernova, even if vacuum mixing angles between active and sterile neutrinos are tiny. Using energetics arguments, this yields limits on the sterile neutrino parameter space that reach down to mixing angles on the order of $\sin^2 2\theta \lesssim 10^{-14}$ and are up to several orders of magnitude stronger than those from X-ray observations. We also compute the flux of $\mathcal{O}(\text{MeV})$ photons expected from the decay of sterile neutrinos produced in supernovae, but find that it is beyond current observational reach even for a nearby supernova.

One of the most auspicious candidate particles for the dark matter in the Universe is the sterile neutrino—an electrically neutral fermion with a mass on the order of keV–MeV that couples to ordinary matter only through a tiny mass mixing with Standard Model (SM) neutrinos [1, 2]. In the simplest sterile neutrino scenarios, it is assumed that the abundance of sterile neutrinos ν_s is zero at the end of inflation, and they are later produced through their mixing with SM (active) neutrinos ν_a [3, 4] (see also [5]). Experimental constraints on the mass of keV sterile neutrinos and their mixing with SM neutrinos arise from the measured DM relic density [6], from Pauli blocking (the Tremaine–Gunn bound) [7, 8], from Lyman- α forests [9], and from X-ray searches for radiative decays of sterile neutrinos $\nu_s \rightarrow \nu_a + \gamma$ [10–13]. From the combination of these constraints, one concludes that the ν_s mass should be $m_s \gtrsim 4$ keV, and its mixing angle with the SM neutrinos should be $\sin^2 2\theta \lesssim 10^{-6}$ in the simple two-flavor approximation.

In this letter, we add a new limit to this inventory of constraints by considering sterile neutrino production in core-collapse supernovae (SN) [14–23]. A supernova develops when a $\gtrsim 9M_\odot$ star runs out of nuclear fuel. The thermal pressure that normally counteracts gravity disappears, and the core of the star collapses into a neutron star. The temperature in the nascent neutron star is $\gtrsim \text{MeV}$, so that a thermal population of (active) neutrinos is produced. These ν_a can oscillate into ν_s , which escape the exploding star unhindered and may carry away significant amounts of energy [16, 20, 24]. Constraints on anomalous energy loss from SN 1987A will thus allow us to constrain the sterile neutrino parameters. Since $\nu_a \rightarrow \nu_s$ conversion can be resonant thanks to the ultra-high matter density $\sim 10^{14} \text{ g/cm}^3$ in the SN core, these limits will be very strong. The flux of sterile neutrinos with $\mathcal{O}(\text{MeV})$ energies escaping from a supernova leads to a flux of secondary gamma rays when they decay, and

we study this flux as well.

Our main results are summarized in fig. 1. The solid orange exclusion region shows that, in the mass range $m_s \sim 2\text{--}80$ keV, limits from energy loss in supernovae surpass previous limits by up to two orders of magnitude in $\sin^2 2\theta$. Note that, unlike the other limits shown in fig. 1, our bounds would still hold if sterile neutrinos are not part of the DM in the Universe. In the following, we discuss in detail how we have obtained our new limits and sensitivity estimates.

Sterile neutrino production in supernovae. We consider a simplified two-flavor oscillation picture with mixing between a sterile neutrino ν_s and one species of active neutrinos ν_x , $x = \mu$ or τ . We do not consider mixing between ν_s and electron neutrinos to avoid complications arising from charged current interactions between ν_e and electrons/positrons. The flavor basis Hamiltonian describing neutrino propagation in matter includes the vacuum oscillation term and a Mikheyev–Smirnov–Wolfenstein (MSW) potential V_x that describes coherent forward scattering of ν_x on the background matter via Z exchange [29–31]:

$$H = \frac{\Delta m^2}{4E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \begin{pmatrix} V_x & 0 \\ 0 & 0 \end{pmatrix}. \quad (1)$$

Here, $\theta \ll 1$ is the ν_s – ν_x mixing angle in vacuum and $\Delta m^2 \simeq m_s^2$ is the mass squared difference between the two mass eigenstates [32]. The MSW potential is $V_x = \pm \sqrt{2}G_F(-N_n/2 + N_{\nu_e} - N_{\bar{\nu}_e})$, where G_F is the Fermi constant and N_n , N_{ν_e} , and $N_{\bar{\nu}_e}$ are the neutron, electron neutrino, and electron antineutrino number densities. The $+$ ($-$) sign corresponds to the potential experienced by neutrinos (antineutrinos). Since $|N_{\nu_e} - N_{\bar{\nu}_e}| \ll N_n/2$, the potential is positive for antineutrinos and negative for neutrinos. Note that we neglect terms that would arise from differences between the ν_x and $\bar{\nu}_x$ number densities because such differences are expected to be small in the

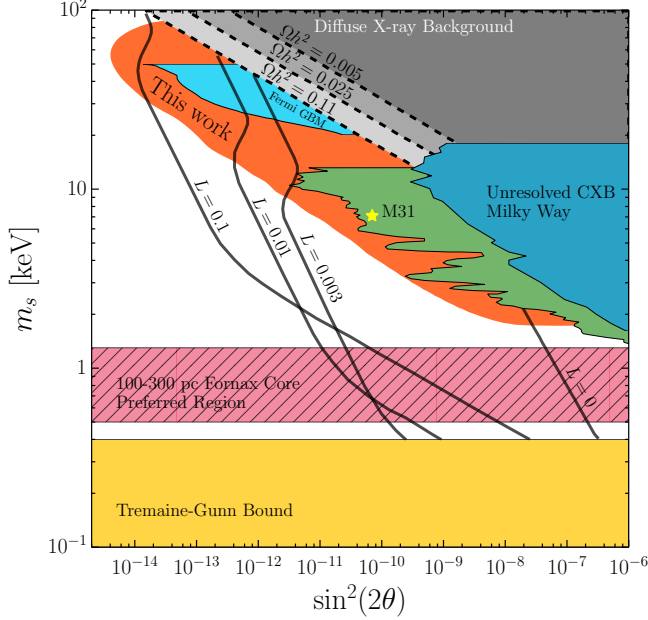


FIG. 1. Supernova bounds on the sterile neutrino mass m_s and mixing $\sin^2 2\theta$ (orange, this work) compared to previous constraints [12, 13, 25] from the Tremaine-Gunn bound [7, 8] (yellow), from X-ray searches in the Andromeda Galaxy M31 [10] (green), from the Fermi GBM all-sky analysis [26] (light blue), and from the galactic [25] (dark blue) and extragalactic [11–13] (gray) diffuse X-ray background. For the latter constraint, we show also how it is modified if sterile neutrinos account for only a fraction of the DM in the Universe. It is understood that the other X-ray limits would shift in a similar way if $\Omega h^2 < 0.11$. We also show in pink the region preferred by the properties of the core of the Fornax dwarf galaxy [27], and as a yellow star the parameter point that could explain the 3.5 keV X-ray line hinted at by refs. [13, 28]. Black curves illustrate the parameter regions in which the Dodelson-Widrow mechanism [3] ($L = 0$) or the Shi-Fuller mechanism [4] with lepton asymmetry $L > 0$ would yield the correct DM relic density $\Omega h^2 = 0.11$.

parameter region where our limits will lie [24]. We have checked that even adding an MSW potential corresponding to a maximal asymmetry does not alter our results significantly. We also neglect the momentum and angular dependence of neutrino self-interactions [33, 34] and instead restrict ourselves to the simplified formalism used in [16, 17, 20]. Since N_n , N_{ν_e} , and $N_{\bar{\nu}_e}$ are extremely large in the supernova core and gradually decrease with radius, most antineutrinos will encounter an MSW resonance on their way out of the exploding star. At the resonance,

$$\cos 2\theta = 2V_x E_{\text{res}}/m_s^2, \quad (2)$$

and the effective mixing angle θ_m in matter becomes maximal [35].

We consider two physically different mechanisms for sterile neutrino production in supernovae:

(i) *Adiabatic flavor conversion at an MSW resonance.*

A ν_x of energy E streaming away from the supernova core can convert to ν_s when the matter density, and thus the MSW potential V_x , has reached the value satisfying the resonance condition, eq. (2). Each point (t, R) in time and space corresponds to a specific value of V_x ; therefore, neutrinos of a specific energy $E_{\text{res}}(t, R)$ are resonantly converted at this point. We take the local neutrino luminosities and spectra and the local matter densities from the simulation of an $8.8M_\odot$ supernova by the Garching group [36] (see also [37–40]).

Hard scattering processes must be rare to give neutrinos sufficient time to convert adiabatically. We therefore require the spatial width of the MSW resonance regions,

$$R_{\text{width}} = 2 \sin 2\theta \left(\frac{1}{V_x} \frac{\partial V_x}{\partial R} \right)^{-1}, \quad (3)$$

to be smaller than the mean free path λ_{mfp} . The number $d\mathcal{N}_s^{\text{MSW}}/dE$ of ν_s in an energy interval $[E, E + dE]$ produced by adiabatic flavor conversion at the MSW resonance is given by [16]

$$\begin{aligned} \frac{d\mathcal{N}_s^{\text{MSW}}}{dE} &= \int_0^t dt' 4\pi R_{\text{res}}^2 n_\nu(t', R_{\text{res}}) \\ &\times f_x(E) P_{\text{res}}(E) \frac{E^2}{\bar{E}^3} \Theta(\lambda_{\text{mfp}} - R_{\text{width}}). \end{aligned} \quad (4)$$

Here, the time integral runs from the time of core bounce ($t' = 0$) until ~ 9 sec later, and $R_{\text{res}}(t', E)$ is the radius at which the resonance energy is E at time t' . The quantity $n_\nu(t', R_{\text{res}})$ is the active neutrino number density at time t' and radius R_{res} , $f_x(E)$ is the energy distribution of active neutrinos, \bar{E} is the average neutrino energy, $P_{\text{res}}(E)$ is the flavor conversion probability at the resonance, and the Heaviside Θ function implements the condition that neutrinos must have enough time between collisions to convert adiabatically. It is crucial that neutrinos do not encounter more than one MSW resonance on their way out of the supernova. (This would be different if we considered mixing between ν_s and ν_e instead of $\nu_{\mu, \tau}$ [18, 19].) Note that we can make the strongly simplifying assumption of radial symmetry, and we also neglect the depletion of active neutrinos by conversion into ν_s . Moreover, we do not need to consider ν_x streaming inwards. They would convert to ν_s at the resonance, then travel through the core, and convert back to ν_x on its far side.

We parameterize $f_x(E)$ as [41]

$$f_x(E) = \frac{(1 + \alpha)^{3+\alpha}}{\Gamma(3 + \alpha)} \left(\frac{E}{\bar{E}} \right)^\alpha \exp \left[-(1 + \alpha) \frac{E}{\bar{E}} \right], \quad (5)$$

with normalization $\int_0^\infty dE E^2 f_x(E) = \bar{E}^3$. (This relation defines \bar{E} .) The “pinching parameter” α describes the degree to which $f_x(E)$ differs from a Maxwell-Boltzmann distribution.

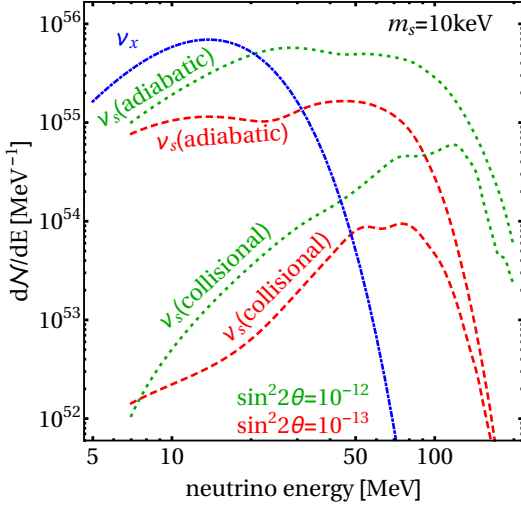


FIG. 2. Spectra of active neutrinos (blue) and sterile neutrinos (green and red) produced in an $8.8M_\odot$ supernova [36]. Contributions from adiabatic flavor conversion and collisional production are shown separately. The ν_s spectrum extends to much higher energies than the ν_x spectrum because flavor conversion occurs in a region where temperatures are much higher than at the last scattering surface of ν_x .

The $\nu_x \rightarrow \nu_s$ conversion probability at the resonance is given by the Landau-Zener formula [16, 17, 35]

$$P_{\text{res}}(E) = 1 - \exp\left[-\frac{\pi^2}{2} \frac{R_{\text{width}}}{L_{\text{osc}}^{\text{res}}}\right], \quad (6)$$

with the oscillation length at the resonance, $L_{\text{osc}}^{\text{res}} \simeq 2\pi/(V_x \sin 2\theta)$.

We find that adiabatic flavor conversion occurs mostly at radii ~ 10 – 15 km, still inside the neutrino sphere at ~ 20 – 30 km. In fig. 2, we compare dN_s^{MSW}/dE to the spectrum of active neutrinos. We see that the ν_s spectrum extends to higher energies because most of the flavor conversion happens in a high-temperature region from which ν_s can stream out freely, while ν_x are still trapped.

(ii) *Collisional production.* Sterile neutrinos can also be produced from a mixed ν_x – ν_s state in hard scatterings on nucleons, electrons, and positrons. We take the interaction rate Γ_x to be approximately equal to the dominant scattering rate on neutrons, and the cross section for this process is computed following [42, 43]. The physical picture for collisional ν_s production is as follows: starting with an ensemble of only ν_x at $t = 0$, each of them soon acquires a small ν_s admixture $\propto \sin^2 2\theta_m$ by oscillation. A collision causes the collapse of the resulting mixed state into either a pure ν_x or a pure ν_s . Afterwards, oscillations start anew, and ν_x are quickly replenished. After many collisions, the ν_s abundance is proportional to $\sin^2 2\theta_m$ and Γ_x .

Up to a factor of $1/2$, this intuitive picture leads to

the correct quantum mechanical Boltzmann equation [1, 3, 15, 44, 45]

$$\frac{\partial}{\partial t} \frac{dn_s}{dE} = \frac{\Gamma_x}{2} \langle P_{\nu_x \rightarrow \nu_s} \rangle \frac{dn_x}{dE}. \quad (7)$$

Here, dn_s/dE and dn_x/dE are the energy spectra of sterile and active neutrinos, respectively. At any given space-time point, $dn_x(t, R, E)/dE$ is related to the distribution function in eq. (5) via $(1/n_x)dn_x/dE = (E^2/\bar{E}^3)f_x(E)$. The averaged oscillation probability $\langle P_{\nu_x \rightarrow \nu_s} \rangle$ is [1]

$$\langle P_{\nu_x \rightarrow \nu_s} \rangle = \frac{1}{2} \frac{\sin^2 2\theta}{(\cos 2\theta - 2V_x E/m_s^2)^2 + \sin^2 2\theta + (\Gamma_x E/m_s^2)^2}. \quad (8)$$

The extra term $(\Gamma_x E/m_s^2)^2$ in the denominator compared to the usual expression for the mixing angle in matter [35] accounts for the suppression of ν_s production when λ_{mfp} is much smaller than the oscillation length, so that oscillations do not have time to develop between collisions (quantum Zeno effect).

Integrating eq. (7) over time and radius leads to the energy spectrum of sterile neutrinos produced collisionally,

$$\frac{dN_s^{\text{coll}}}{dE} = \int_0^t dt' \int_0^{R_{\text{core}}} dR' 4\pi R'^2 \frac{\Gamma_x}{2} \langle P_{\nu_x \rightarrow \nu_s} \rangle \frac{dn_x}{dE}. \quad (9)$$

We again evaluate dN_s/dE numerically using the data from [36]. The resulting ν_s spectra, shown in fig. 2, can be harder than the ones from adiabatic production because the collisional production rate depends on Γ_x , which grows proportional to E^2 .

Constraints from supernova luminosity. We can constrain the energy output in sterile neutrinos from SN 1987A by comparing the observed energy output in active neutrinos of $\mathcal{E}_a = \text{few} \times 10^{53}$ ergs [46, 47] to the gravitational energy released in the collapse of a stellar core at the Chandrasekhar mass, which is also on the order of $\mathcal{E}_{\text{tot}} = \text{few} \times 10^{53}$ ergs [36, 48]. If a substantial fraction of \mathcal{E}_{tot} was carried away by sterile neutrinos, the observed \mathcal{E}_a could not be explained [49]. We therefore consider the ratio $\mathcal{R}(\sin^2 2\theta, m_s) \equiv \mathcal{E}_s(\sin^2 2\theta, m_s)/\mathcal{E}_{\text{tot}}$. We assume that \mathcal{R} depends only weakly on the mass and type of the progenitor star, so that the values obtained for the supernova simulated in [36] are a good proxy for SN 1987A. Our computation of ν_s production is only self-consistent for $\mathcal{R} \ll 1$ because we neglect depletion of active neutrinos. We nevertheless extrapolate it to larger values and set a limit by requiring $\mathcal{R} < 1$. The justification for this is that the associated uncertainty in our results is on the same order as the uncertainty of the predicted and measured energy outputs from SN 1987A. We have verified this assumption by rescaling in each time step of our calculation the active neutrino number densities to account for the energy carried away by sterile

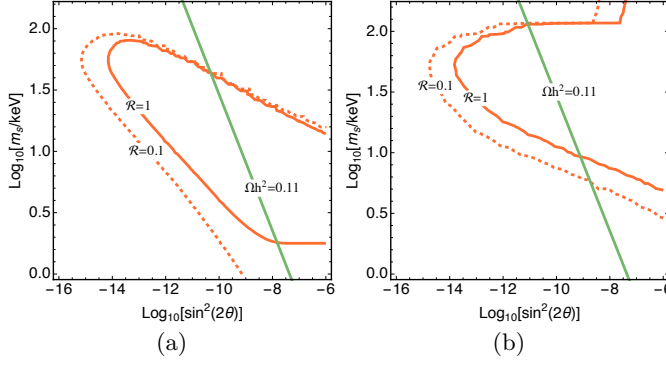


FIG. 3. Constraints on the sterile neutrino parameter space from energy loss in supernovae, considering (a) adiabatic $\nu_x \rightarrow \nu_s$ conversion only or (b) collisional ν_s production only. The solid and dotted orange curves correspond to different assumptions on the maximum allowed energy loss, expressed here in terms of the ratio \mathcal{R} of the energy output in sterile neutrinos and the total energy output. For comparison, we also show in green the parameters for which the Dodelson-Widrow mechanism [3] predicts the correct relic abundance of ν_s .

neutrinos up to this time. Doing so modifies our limit by $\lesssim 30\%$.

Our limits on the ν_s parameter space are shown in fig. 3 for adiabatically and collisionally produced ν_s separately, and in fig. 1 for the combination of both production mechanisms (requiring $\mathcal{R} < 1$). Thanks to MSW enhancement, our constraints reach down to $\sin^2 2\theta \sim 10^{-14}$ at $m_s \sim 10$ –100 keV, surpassing all other limits in this mass range.

The shape of the exclusion regions in fig. 3 can be understood as follows. For adiabatic conversion at small m_s , the oscillation length at the MSW resonance $L_{\text{osc}}^{\text{res}}$ is large, making flavor conversion non-adiabatic according to eq. (6). At large $m_s \gtrsim 100$ keV, the resonance condition of eq. (2) cannot be satisfied. At $m_s \sim \text{few} \times 10$ keV, adiabatic flavor conversion is most effective at low $\sin^2 2\theta \sim 10^{-14}$. For larger $\sin^2 2\theta$, the radial width R_{width} of the resonance region becomes too large, so that neutrinos scatter before having a chance to convert. Also collisional production is most effective when the mixing angle in matter is MSW-enhanced. At $m_s \lesssim 10$ keV, the resonance condition of eq. (2) is fulfilled only in the outer regions of the supernova, where the scattering rate is too low for effective collisional production. At $m_s \gtrsim 100$ keV, the resonance condition is never satisfied.

Photon flux from $\nu_s \rightarrow \nu_a \gamma$. Sterile neutrinos, once produced, decay to photons via $\nu_s \rightarrow \nu_a \gamma$, a process mediated by loop diagrams involving charged leptons and W bosons. The decay rate is [50]

$$\Gamma_{\nu_s \rightarrow \nu_a \gamma} = 1.38 \cdot 10^{-29} \text{ sec}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}} \right) \left(\frac{m_s}{1 \text{ keV}} \right)^5. \quad (10)$$

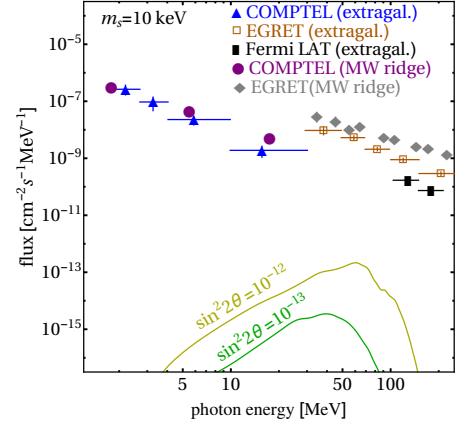


FIG. 4. Photon flux from the decay of sterile neutrinos produced in a nearby ($d = 1$ kpc) supernova for different benchmark points in the m_s – $\sin^2 2\theta$ plane. We compare to observed spectra of diffuse gamma rays from COMPTEL [53–55], EGRET [56–58], and Fermi-LAT [59], assuming angular bin sizes of 1 degree for COMPTEL, 5 degrees for EGRET, and 3 degrees for Fermi-LAT [60].

Thus, if ν_s are abundantly produced in a supernova, we expect the explosion to be accompanied by a flux of energetic ($\mathcal{O}(1$ –100 MeV)) secondary gamma rays. Photons in this energy range are not normally expected from a supernova or supernova remnant, both of which emit X-rays only at energies $\lesssim 10$ keV [51, 52]. The arrival times of the gamma rays from ν_s decay are spread out over a time interval

$$\Delta t \simeq 3.6 \text{ hrs} \times \left(\frac{d}{1 \text{ kpc}} \right) \left(\frac{m_s}{1 \text{ keV}} \right)^2 \left(\frac{1 \text{ MeV}}{E_\gamma} \right)^2, \quad (11)$$

where d is the distance to the supernova and E_γ is the gamma ray energy (which is just half the ν_s energy, $E_\gamma = E_\nu/2$). Sterile neutrinos decaying immediately after their production lead to gamma rays that reach the Earth at the same time as the active neutrino burst. Gamma rays from ν_s decaying only after travelling a distance $\simeq d$ are delayed by Δt .

The photon flux from ν_s decay in units of $\text{cm}^{-2} \text{ sec}^{-1} \text{ MeV}^{-1}$ is given by

$$\frac{d\phi_\gamma(E_\gamma)}{dE_\gamma} = \frac{2}{4\pi \Delta t d^2} [1 - \exp(-\frac{d}{\gamma} \Gamma_{\nu_s \rightarrow \nu_a \gamma})] \frac{dN_{\nu_s}(E_\nu)}{dE_\nu}, \quad (12)$$

where $\gamma = 2E_\gamma/m_s$ is the Lorentz boost factor. The factor in parenthesis accounts for the ν_s decay probability. Note that the sterile neutrino spectrum $dN_{\nu_s}(E_\nu)/dE_\nu$ is evaluated at $E_\nu = 2E_\gamma$.

We plot $d\phi_\gamma(E_\gamma)/dE_\gamma$ for two sets of benchmark parameters in fig. 4, and the total gamma ray flux as a function of $\sin^2 2\theta$ and m_s is shown in fig. 5. In both figures, we have chosen $d = 1$ kpc. As expected from

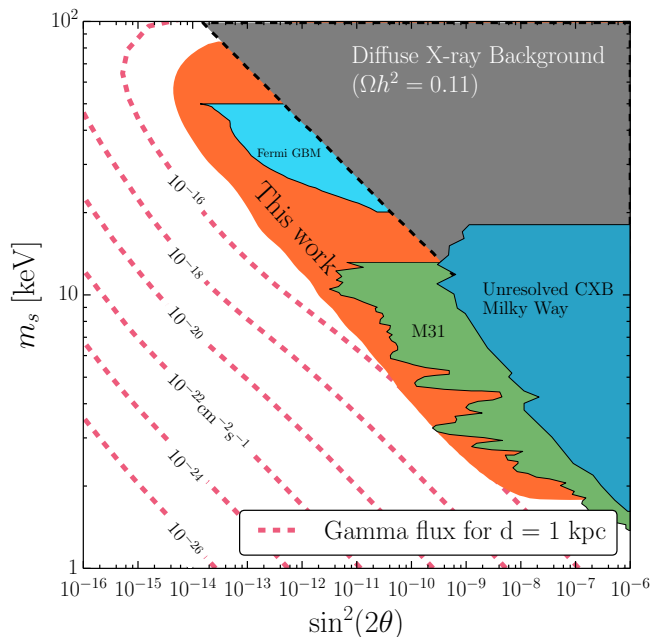


FIG. 5. Expected photon flux from the decay of sterile neutrinos produced in a supernova at a distance $d = 1$ kpc. We compare to our new energy loss limits from fig. 1 (orange region) and to constraints from X-ray searches [10–13, 25, 26] (green, dark blue, gray, and light blue regions).

fig. 2, and taking into account $E_\gamma = E_\nu/2$, the photon spectrum peaks at $E \sim 10\text{--}100$ MeV. Comparing the expected photon spectrum to the diffuse astrophysical gamma ray background measured by COMPTEL [53–55], EGRET [56–58] and Fermi-LAT [59], we find that the signal is still several orders of magnitude below the uncertainty on the background. Most likely, a direct observation of the ν_s -induced photon signal is therefore beyond the scope of even the next generation of Compton telescopes [61–63] and would require a factor $\sim 10^5$ improvement compared to the projected sensitivity of ComPair [62].

Summary. In conclusion, we have computed the flux of hypothetical keV–MeV sterile neutrinos ν_s from a supernova. We have constrained the ν_s parameter space using energy loss arguments (fig. 1), and we have estimated the gamma ray flux from ν_s produced in a nearby supernova. Directions for future work include a more detailed calculation of the ν_s flux from a supernova, going beyond the two flavor approximation and with a more detailed treatment of collective effects. We moreover plan to investigate how our results depend on the mass of the progenitor star [64].

Acknowledgments. We are indebted to Georg Raffelt and Ninetta Saviano for many useful comments on the manuscript, and to Thomas Janka and his collaborators for providing the data from [36] in machine-readable form. We would also like to thank Markus Ack-

ermann and John Beacom for very useful discussions. VB would like to thank the Wisconsin IceCube Particle Astrophysics Center (WIPAC) for hospitality. The work of VB and JK is supported by the German Research Foundation (DFG) under Grant Nos. KO 4820/1–1 and FOR 2239 and by the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No. 637506, “ ν Directions”). VB is supported by the DFG Graduate School Symmetry Breaking in Fundamental Interactions (GRK 1581). Additional support has been provided by the Cluster of Excellence “Precision Physics, Fundamental Interactions and Structure of Matter” (PRISMA – EXC 1098), grant No. 05H12UME of the German Federal Ministry for Education and Research (BMBF). CA was supported in part by the National Science Foundation (OPP-0236449, NSF-PHY-1505858, and PHY-0969061) and by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

-
- [1] K. Abazajian, G. M. Fuller, and M. Patel, *Sterile neutrino hot, warm, and cold dark matter*, *Phys. Rev. D* **64** (2001) 023501, [[astro-ph/0101524](#)].
 - [2] A. Kusenko, *Sterile neutrinos: The Dark side of the light fermions*, *Phys.Rept.* **481** (2009) 1–28, [[arXiv:0906.2968](#)].
 - [3] S. Dodelson and L. M. Widrow, *Sterile-neutrinos as dark matter*, *Phys.Rev.Lett.* **72** (1994) 17–20, [[hep-ph/9303287](#)].
 - [4] X.-D. Shi and G. M. Fuller, *A New dark matter candidate: Nonthermal sterile neutrinos*, *Phys.Rev.Lett.* **82** (1999) 2832–2835, [[astro-ph/9810076](#)].
 - [5] A. Merle, V. Niro, and D. Schmidt, *New Production Mechanism for keV Sterile Neutrino Dark Matter by Decays of Frozen-In Scalars*, [arXiv:1306.3996](#).
 - [6] **Planck** Collaboration, P. A. R. Ade et al., *Planck 2015 results. XIII. Cosmological parameters*, [arXiv:1502.01589](#).
 - [7] S. Tremaine and J. E. Gunn, *Dynamical Role of Light Neutral Leptons in Cosmology*, *Phys. Rev. Lett.* **42** (1979) 407–410.
 - [8] D. Iakubovskyi, *Constraining properties of dark matter particles using astrophysical data*. PhD thesis, Leiden University, February, 2013.
 - [9] J. Baur, N. Palanque-Delabrouille, C. Yche, C. Magneville, and M. Viel, *Lyman-alpha Forests cool Warm Dark Matter*, in *SDSS-IV Collaboration Meeting, July 20–23, 2015*, 2015. [arXiv:1512.01981](#).
 - [10] S. Horiuchi, P. J. Humphrey, J. Onorbe, K. N. Abazajian, M. Kaplinghat, et al., *Sterile neutrino dark matter bounds from galaxies of the Local Group*, [arXiv:1311.0282](#).
 - [11] A. Boyarsky, A. Neronov, O. Ruchayskiy, and M. Shaposhnikov, *Constraints on sterile neutrino as a dark matter candidate from the diffuse x-ray background*, *Mon. Not. Roy. Astron. Soc.* **370** (2006) 213–218, [[astro-ph/0512509](#)].

- [12] K. N. Abazajian, *Detection of Dark Matter Decay in the X-ray*, [arXiv:0903.2040](#).
- [13] E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, et al., *Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters*, [arXiv:1402.2301](#).
- [14] K. Kainulainen, J. Maalampi, and J. T. Peltoniemi, *Inert neutrinos in supernovae*, *Nucl. Phys.* **B358** (1991) 435–446.
- [15] G. Raffelt and G. Sigl, *Neutrino flavor conversion in a supernova core*, *Astropart. Phys.* **1** (1993) 165–184, [[astro-ph/9209005](#)].
- [16] X. Shi and G. Sigl, *A Type II supernovae constraint on electron-neutrino - sterile-neutrino mixing*, *Phys. Lett.* **B323** (1994) 360–366, [[hep-ph/9312247](#)]. [Erratum: *Phys. Lett.* B324,516(1994)].
- [17] H. Nunokawa, J. T. Peltoniemi, A. Rossi, and J. W. F. Valle, *Supernova bounds on resonant active sterile neutrino conversions*, *Phys. Rev.* **D56** (1997) 1704–1713, [[hep-ph/9702372](#)].
- [18] J. Hidaka and G. M. Fuller, *Dark matter sterile neutrinos in stellar collapse: Alteration of energy/lepton number transport and a mechanism for supernova explosion enhancement*, *Phys. Rev.* **D74** (2006) 125015, [[astro-ph/0609425](#)].
- [19] J. Hidaka and G. M. Fuller, *Sterile Neutrino-Enhanced Supernova Explosions*, *Phys. Rev.* **D76** (2007) 083516, [[arXiv:0706.3886](#)].
- [20] G. G. Raffelt and S. Zhou, *Supernova bound on keV-mass sterile neutrinos reexamined*, *Phys. Rev.* **D83** (2011) 093014, [[arXiv:1102.5124](#)].
- [21] M.-R. Wu, T. Fischer, L. Huther, G. Martinez-Pinedo, and Y.-Z. Qian, *Impact of active-sterile neutrino mixing on supernova explosion and nucleosynthesis*, *Phys. Rev.* **D89** (2014), no. 6 061303, [[arXiv:1305.2382](#)].
- [22] M. L. Warren, M. Meixner, G. Mathews, J. Hidaka, and T. Kajino, *Sterile neutrino oscillations in core-collapse supernova simulations*, [arXiv:1405.6101](#).
- [23] M. Warren, G. J. Mathews, M. Meixner, J. Hidaka, and T. Kajino, *A review of the impact of sterile neutrino dark matter on core-collapse supernovae*, [arXiv:1603.05503](#).
- [24] G. G. Raffelt, *Astrophysical methods to constrain axions and other novel particle phenomena*, *Phys. Rept.* **198** (1990) 1–113.
- [25] K. N. Abazajian, M. Markevitch, S. M. Koushiappas, and R. C. Hickox, *Limits on the Radiative Decay of Sterile Neutrino Dark Matter from the Unresolved Cosmic and Soft X-ray Backgrounds*, *Phys. Rev.* **D75** (2007) 063511, [[astro-ph/0611144](#)].
- [26] K. C. Y. Ng, S. Horiuchi, J. M. Gaskins, M. Smith, and R. Preece, *Improved Limits on Sterile Neutrino Dark Matter using Full-Sky Fermi-GBM Data*, [arXiv:1504.04027](#).
- [27] L. E. Strigari, J. S. Bullock, M. Kaplinghat, A. V. Kravtsov, O. Y. Gnedin, K. Abazajian, and A. A. Klypin, *A large dark matter core in the Fornax dwarf spheroidal galaxy?*, *Astrophys. J.* **652** (2006) 306–312, [[astro-ph/0603775](#)].
- [28] A. Boyarsky, O. Ruchayskiy, D. Iakubovskiy, and J. Franse, *An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster*, [arXiv:1402.4119](#).
- [29] L. Wolfenstein, *Neutrino Oscillations in Matter*, *Phys. Rev.* **D17** (1978) 2369–2374.
- [30] S. P. Mikheev and A. Yu. Smirnov, *Resonance Amplification of Oscillations in Matter and Spectroscopy of Solar Neutrinos*, *Sov. J. Nucl. Phys.* **42** (1985) 913–917. [*Yad. Fiz.* 42,1441(1985)].
- [31] S. P. Mikheev and A. Yu. Smirnov, *Resonant amplification of neutrino oscillations in matter and solar neutrino spectroscopy*, *Nuovo Cim.* **C9** (1986) 17–26.
- [32] In this paper, we refer to m_s as the sterile neutrino mass, even though we mean of course the mass of the heavy mass eigenstate which is mostly a ν_s , with only a tiny admixture of ν_x .
- [33] H. Duan, G. M. Fuller, and Y.-Z. Qian, *Collective Neutrino Oscillations*, *Ann. Rev. Nucl. Part. Sci.* **60** (2010) 569–594, [[arXiv:1001.2799](#)].
- [34] B. Dasgupta and A. Dighe, *Collective three-flavor oscillations of supernova neutrinos*, *Phys. Rev.* **D77** (2008) 113002, [[arXiv:0712.3798](#)].
- [35] E. K. Akhmedov, *Neutrino physics*, [hep-ph/0001264](#).
- [36] L. Hüpdepohl, B. Müller, H. Janka, A. Marek, and G. G. Raffelt, *Neutrino Signal of Electron-Capture Supernovae from Core Collapse to Cooling*, *Physical Review Letters* **104** (June, 2010) 251101–+, [[arXiv:0912.0260](#)]. machine-readable data from <http://wwwmpa.mpa-garching.mpg.de/ccsnarchive/data/Huedepohl2010-data/index.html>; we use results for the model with full neutrino interactions (Sf).
- [37] M. Rampp and H. T. Janka, *Radiation hydrodynamics with neutrinos: Variable Eddington factor method for core collapse supernova simulations*, *Astron. Astrophys.* **396** (2002) 361, [[astro-ph/0203101](#)].
- [38] M. Liebendoerfer, M. Rampp, H. T. Janka, and A. Mezzacappa, *Supernova simulations with Boltzmann neutrino transport: A Comparison of methods*, *Astrophys. J.* **620** (2005) 840–860, [[astro-ph/0310662](#)].
- [39] A. Marek, H. Dommelmeier, H. T. Janka, E. Muller, and R. Buras, *Exploring the relativistic regime with Newtonian hydrodynamics: An Improved effective gravitational potential for supernova simulations*, *Astron. Astrophys.* **445** (2006) 273, [[astro-ph/0502161](#)].
- [40] R. Buras, M. Rampp, H. T. Janka, and K. Kifonidis, *Two-dimensional hydrodynamic core-collapse supernova simulations with spectral neutrino transport. 1. Numerical method and results for a 15 solar mass star*, *Astron. Astrophys.* **447** (2006) 1049–1092, [[astro-ph/0507135](#)].
- [41] M. T. Keil, G. G. Raffelt, and H.-T. Janka, *Monte Carlo study of supernova neutrino spectra formation*, *Astrophys. J.* **590** (2003) 971–991, [[astro-ph/0208035](#)].
- [42] C. Giunti and C. W. Kim, *Fundamentals of Neutrino Physics and Astrophysics*. Oxford University Press, Oxford, UK, 2007. ISBN 978-0-19-850871-7.
- [43] J. Peltoniemi, “The ultimate neutrino page.” <http://cupp oulu.fi/neutrino/>.
- [44] L. Stodolsky, *On the Treatment of Neutrino Oscillations in a Thermal Environment*, *Phys. Rev.* **D36** (1987) 2273.
- [45] M. J. Thomson, *Damping of quantum coherence by elastic and inelastic processes*, *Phys. Rev. A* **45** (Feb, 1992) 2243–2249.
- [46] T. J. Loredo and D. Q. Lamb, *Bayesian analysis of neutrinos observed from supernova SN-1987A*, *Phys.*

- Rev. D* **65** (2002) 063002, [[astro-ph/0107260](#)].
- [47] G. Pagliaroli, F. Vissani, M. L. Costantini, and A. Ianni, *Improved analysis of SN1987A antineutrino events*, *Astropart. Phys.* **31** (2009) 163–176, [[arXiv:0810.0466](#)].
- [48] K. Zuber, *Neutrino Physics, Second Edition*. Series in High Energy Physics, Cosmology and Gravitation. Taylor & Francis, 2011.
- [49] A similar constraint could also be obtained by considering the observed duration of the neutrino emission from SN 1987A. Efficient production of sterile neutrinos would expedite the cooling of the supernova core, shortening the neutrino burst [20, 24].
- [50] Z. Xing and S. Zhou, *Neutrinos in Particle Physics, Astronomy and Cosmology*. Advanced Topics in Science and Technology in China. Springer Berlin Heidelberg, 2011.
- [51] A. M. Soderberg et al., *An Extremely Luminous X-ray Outburst Marking the Birth of a Normal Supernova*, *Nature* **453** (2008) 469–474, [[arXiv:0802.1712](#)].
- [52] J. Vink, *Supernova remnants: the X-ray perspective*, *Astron. Astrophys. Review* **20** (Dec., 2012) 49, [[arXiv:1112.0576](#)].
- [53] A. W. Strong, K. Bennett, H. Bloemen, R. Diehl, W. Hermsen, D. Morris, V. Schoenfelder, J. G. Stacy, C. de Vries, M. Varendorff, C. Winkler, and G. Youssefi, *Diffuse continuum gamma rays from the Galaxy observed by COMPTEL*, *Astron. and Astrophys.* **292** (Dec., 1994) 82–91.
- [54] S. C. Kappadath, J. Ryan, K. Bennett, H. Bloemen, D. Forrest, W. Hermsen, R. M. Kippen, M. McConnell, V. Schoenfelder, R. van Dijk, M. Varendorff, G. Weidenspointner, and C. Winkler, *The preliminary cosmic diffuse γ -ray spectrum from 800 keV to 30 MeV measured with COMPTEL.*, *Astron. Astrophys. Proc. Suppl.* **120** (Dec., 1996) 619–622.
- [55] R. L. Kinzer, W. R. Purcell, and J. D. Kurfess, *Gamma-Ray Emission from the Inner Galactic Ridge*, *Astrophys. J.* **515** (Apr., 1999) 215–225.
- [56] S. D. Hunter, D. L. Bertsch, J. R. Catelli, T. M. Dame, S. W. Digel, B. L. Dingus, J. A. Esposito, C. E. Fichtel, R. C. Hartman, G. Kanbach, D. A. Kniffen, Y. C. Lin, H. A. Mayer-Hasselwander, P. F. Michelson, C. von Montigny, R. Mukherjee, P. L. Nolan, E. Schneid, P. Sreekumar, P. Thaddeus, and D. J. Thompson, *EGRET Observations of the Diffuse Gamma-Ray Emission from the Galactic Plane*, *Astrophys. J.* **481** (May, 1997) 205–240.
- [57] **EGRET** Collaboration, P. Sreekumar et al., *EGRET observations of the extragalactic gamma-ray emission*, *Astrophys. J.* **494** (1998) 523–534, [[astro-ph/9709257](#)].
- [58] P. Sreekumar, F. W. Stecker, and S. C. Kappadath, *The extragalactic diffuse gamma-ray emission*, *AIP Conf. Proc.* **410** (1997) 344, [[astro-ph/9709258](#)].
- [59] **Fermi-LAT** Collaboration, M. Ackermann et al., *The spectrum of isotropic diffuse gamma-ray emission between 100 MeV and 820 GeV*, *Astrophys. J.* **799** (2015) 86, [[arXiv:1410.3696](#)].
- [60] V. Schönfelder and G. Kanbach, *Observing Photons in Space: A Guide to Experimental Space Astronomy*, ch. Imaging through Compton scattering and pair creation, pp. 225–242. Springer New York, New York, NY, 2013. available from <http://ftp.issibern.ch/forads/sr-009-11.pdf>.
- [61] S. D. Hunter et al., *A Pair Production Telescope for Medium-Energy Gamma-Ray Polarimetry*, *Astropart. Phys.* **59** (2014) 18–28, [[arXiv:1311.2059](#)].
- [62] A. A. Moiseev et al., *Compton-Pair Production Space Telescope (ComPair) for MeV Gamma-ray Astronomy*, [[arXiv:1508.07349](#)].
- [63] M. Tavani et al., “The gamma-ray sky with astrogam: Second astrogam workshop.” .
- [64] C. A. Argüelles, V. Brdar, and J. Kopp. in preparation.